

Spectral Diagnostics for Early-Type Stars in Support of High-Resolution Satellite Observations

NASA Long Term Space Astrophysics Program
Grant Number NAG5-9461

PI: Dr. Joseph J. MacFarlane
Prism Computational Sciences
16 N. Carroll Street
Suite 950
Madison, WI 53703

I. Introduction

The purpose of this report is: (1) to provide a summary of work performed in the first year of this 5-year grant; and (2) to list the areas of research we anticipate working on during the next year of this grant.

II. Summary of First Year's Work

The following briefly summarizes the work performed during Year 1 of this grant. A list of papers and conference abstracts from this year is listed in Section III.

Analysis and Modeling of High Resolution X-Ray Spectra from ζ Pup and δ Ori:

High-resolution X-ray spectra have recently been obtained using the Chandra X-ray Satellite Observatory for the two hot supergiant stars ζ Pup and δ Ori. The spectra show the presence of strong K-shell line emission from O, Ne, Mg, Si, and S, as well as strong L-shell line emission from Fe. Initial examination of the spectra indicates that the lines are significantly broader than what would be expected for a stationary plasma, and appear to be consistent with Doppler-broadened emission from hot plasma forming in shock-heated regions embedded in the wind (see Figure 1). Chandra has sufficient spectral resolution to study the velocity structure of isolated X-ray line profiles. Our analysis for ζ Pup has shown blue-shifted and skewed line profiles, providing the most direct evidence that the X-ray source is embedded in the stellar wind. The sensitivity of the He-like *fir* (forbidden-intercombination-resonance) lines to a strong UV radiation field is used to estimate the radial distances at which lines of O VII, Ne IX, Mg XI, Si XIII, and S XV originate. A paper describing our initial analysis of the ζ Pup spectrum has been submitted to the Astrophysical Journal (Cassinelli et al. 2001).

As part of our analysis, we performed numerical simulations of spectra using our 1D collisional-radiative spectral analysis code (NLVERT), which utilizes atomic data generated by the ATBASE atomic physics package. Here, we have investigated the temperature and density characteristics of the X-ray emitting plasma, detailed line profiles, and the sensitivity of *fir* line complex spectra to the stellar UV radiation field (see Figures 2 and 3). Results from this analysis were presented at the High Energy Astrophysics Division Meeting in November 2000. It is expected a write-up of these numerical simulations will be submitted for publication in the coming year.

High-resolution Chandra spectral data has also been obtained for the O9 Ia star δ Ori. Preliminary analysis of this spectral data was presented by UW graduate student N. Miller at the High Energy Astrophysics Division Meeting in November 2000. It is expected that results of this analysis will be submitted for publication in the coming year.

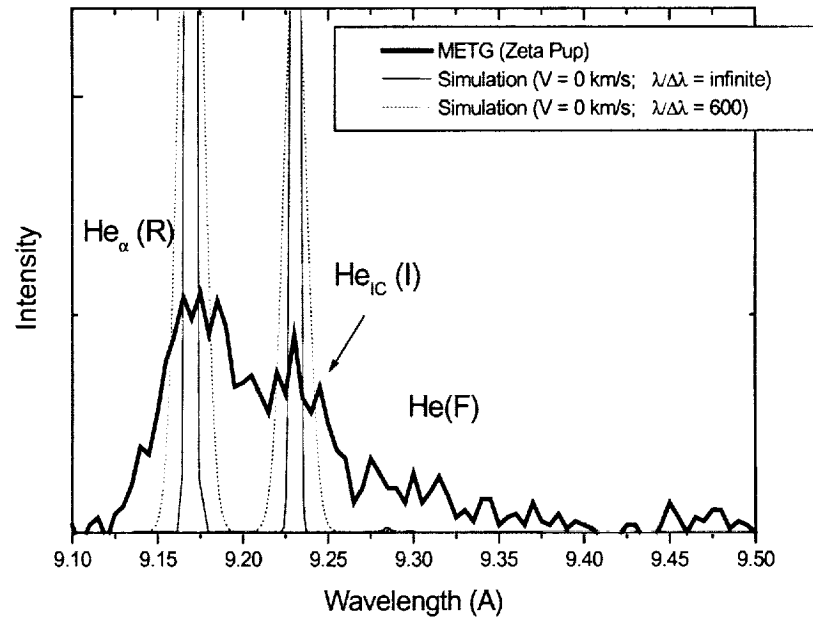


Figure 1. Comparison of observed spectrum for ζ Pup with numerical simulations of the *fir* complex for He-like Mg (the dashed curve including Chandra instrumental broadening). These results indicate that the X-ray spectral lines cannot be produced by a stationary plasma, but instead are produced by Doppler broadening in the wind.

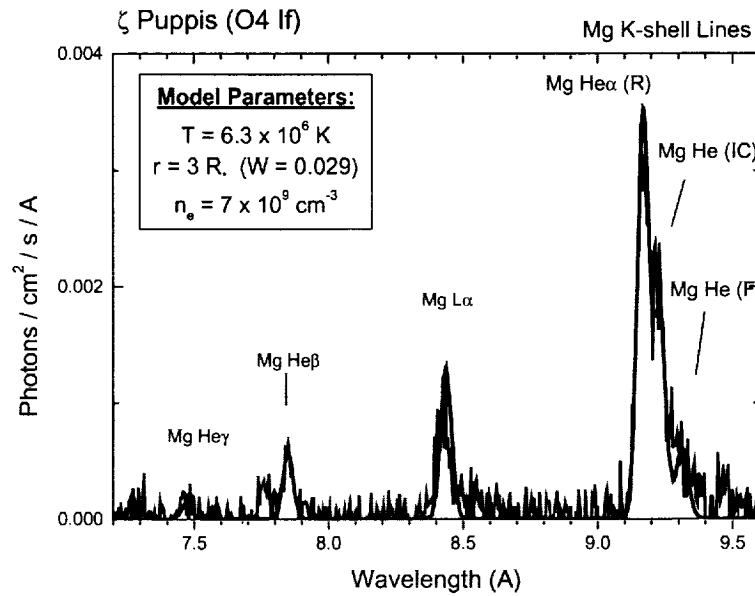


Figure 2. Comparison of observed spectrum for ζ Pup with numerical simulations of He-like and H-like Mg. The blue curve represents the simulated spectrum with a temperature of 6.3×10^6 K, an electron density of $7 \times 10^9 \text{ cm}^{-3}$, and a photospheric UV radiation field that is consistent with the X-ray emitting plasma being at a radius of 3 stellar radii.

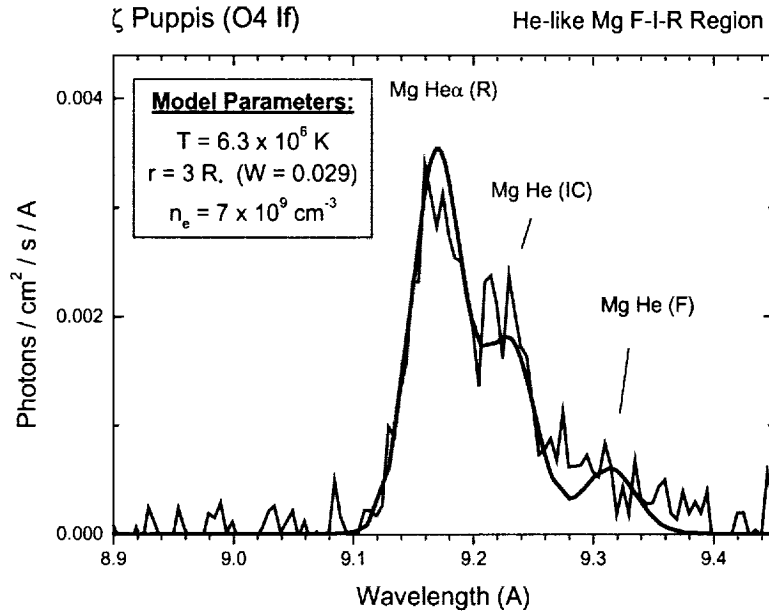


Figure 3. Same as Figure 2, but showing the He-like fir spectral region in detail. The simulated spectrum, which includes Doppler-broadened lines, is seen to be in good agreement with the observed spectrum.

Analysis of High Resolution X-Ray Spectra from ζ Ori:

High-resolution X-ray spectra have also recently been obtained using the Chandra X-ray Satellite Observatory for the ζ Ori. This work suggested that the X-ray emission from Si XIII is consistent with emission from a relatively dense plasma which is located close to the star. Details of this analysis has been submitted for publication to the Astrophysical Journal (Waldron & Cassinelli, 2001).

Ionization Structure and Line Profiles for B Star Winds:

Results from a wind ionization study for rapidly-rotation B stars was recently submitted for publication to the Astrophysical Journal (Bjorkman, Abbott, & MacFarlane, 2001). In this work, the two-dimensional structure for near main-sequence B stars was investigated, as well as the implications for observed line profiles. It was found that there is a rapid radial ionization gradient in the weak winds of B stars, and that this rapid ionization is responsible for producing the characteristic shape of their UV wind-line profiles. Results were presented showing the influence of mass loss rate and viewing angle on the line profiles.

Modeling X-ray Variability in Hot Star Structured Atmospheres:

A study describing the X-ray production in the atmospheres of hot, early-type stars was submitted for publication by Oskinova, Ignace, Brown, and Cassinelli (2001). This study showed that the apparent lack of X-ray variability on short (~ hour) time scales do not contradict shocks models for X-ray production. The character of the X-ray variability was found to depend on the frequency with which hot zones are generated, the scale of the cool wind opacity to X-rays, and the wind flow parameters such as mass loss rate and terminal speed.

III. Publications and Abstracts

- 2001 Cassinelli, J. P., Miller, N., Waldron, W., MacFarlane, J. J., and Cohen, D. H.
 "Chandra Detection of Doppler Shifted X-ray Line Profiles from the Wind of ζ Pup ,"
 Submitted to Astrophysical Journal.

- 2001 Bjorkman, J. E., Abbott, B., and MacFarlane
 "Ionization Structure, Line Profiles, and Mass Loss for Rapidly-Rotating Near Main-Sequence B
 Star Winds ,"
 Submitted to Astrophysical Journal.

- 2001 Waldron, W., and Cassinelli, J. P.
 "Chandra Discovers a Very High Density X-ray Plasma on the O-Star ζ Orionis,"
 Submitted to Astrophysical Journal.

- 2001 Oskinova, W., Ignace, R., Brown, J. C., and Cassinelli, J. P.
 "Modeling X-ray Variability in the Structured Atmospheres of Hot Stars,"
 Submitted to Astronomy and Astrophysics.

- 2000 MacFarlane, J. J., Wang, P., Cassinelli, J. P., Miller, N., and Cohen, D. H.
 "Simulations of Chandra X-ray Spectral Observations of ζ Pup ,"
 Presented at the High Energy Astrophysics Division Meeting, Honolulu, HA (November 2000).

- 2000 Cassinelli, J. P., Miller, N., and MacFarlane, J. J.

"HETG Observations of Zeta Puppis ,"

Presented at the High Energy Astrophysics Division Meeting, Honolulu, HA (November 2000).

2000 Miller, N., Cassinelli, J. P., and MacFarlane, J. J.

"HETG Observations of Delta Ori ,"

Presented at the High Energy Astrophysics Division Meeting, Honolulu, HA (November 2000).

IV. Research Plans for Year 2

During the next year of this grant, we anticipate performing detailed modeling of X-ray spectra obtained for several early-type stars: ζ Pup, δ Ori, and τ Sco.

The main tasks associated with this modeling will include:

- Modeling the effects of the overlying cool wind on the observed spectra.
- Studying in greater detail the location in the wind where the X-rays originate.
- Obtaining estimates of the total (wind) X-ray luminosity, and comparing it to the observed flux. (It is expected that many of the X-rays emitted are absorbed in the cool wind before they can escape the stellar environment.)
- Analyzing the spectra emission lines from several elements to place greater constraints on emission measure distribution.
- Determining constraints on the spatial dependence of the hot plasma temperature.
- Comparing spectra from the different stars to attempt to discern differences in the plasma emission properties, as well as the physical processes responsible for heating these plasmas.

In doing this work, results will be presented at relevant conferences and workshops, and published in appropriate journals.